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FORESTRY SCIENCE

Calibration of the Pilodyn instrument for the indirect *in situ* determination of the basic wood density of balsa

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ABSTRACT: *Balsa wood is used widely in the nautical, aeronautical and wind-energy industries because of its low-density and high-resistance. In the Brazilian state of Mato Grosso, speculative producers with little knowledge of the culture have established balsa plantations using non-standardized and non-selected seedlings. In this sense, research is needed to improve balsa cultivation under Brazilian conditions to better explore the resource. The present study evaluated the efficiency of the Pilodyn instrument for the indirect determination of the basic wood density (BWD) of balsa. Twenty 12-year old balsa trees cultivated in Alta Floresta, Mato Grosso, were probed with the Pilodyn instrument on both north and south faces of the trunk at the base and at 1.30 and 3.10 m from the ground. Wood discs were subsequently collected from the probed sites and BWD determined according to the water-immersion method. Data were submitted to the Shapiro-Wilk normality test followed by analysis of variance and Pearson's correlation analysis with α=0.05. The BWD of balsa decreased in the direction from the base to the top of the tree. The penetration depth of the Pilodyn probe was inversely proportional to BWD with a correlation that was strong (R^2=0.72) at heights of 1.30 and 3.10 m but considered weak (R^2=0.46) at the base of the trunk. The reliability of the Pilodyn method was sufficient to allow the development of a linear equation that could be applied for the indirect determination of the BWD of balsa based on the penetration depth of the Pilodyn probe assessed at 1.30 m from the ground.*
Key words: *Ochroma pyramidale, forest improvement, silviculture.*

Calibração do instrumento Pilodyn para determinação indireta *in situ* da densidade básica da madeira de pau-de-balsa

RESUMO: *O pau-de-balsa é amplamente utilizado nas indústrias náutica, aeronáutica e de energia eólica devido à sua baixa densidade. No estado de Mato Grosso, produtores especulativos de balsa têm estabelecido plantios sem conhecimento sólido da cultura usando mudas não padronizadas e não selecionadas. Pesquisas são necessárias para melhorar o cultivo de balsa sob condições brasileiras para melhor explorar este recurso. O presente estudo teve como objetivo avaliar a eficiência do instrumento Pilodyn para a determinação indireta da densidade básica da madeira (DBM) de balsa. Vinte árvores de 12 anos de idade cultivadas em Alta Floresta, Mato Grosso, foram avaliadas com o instrumento Pilodyn nas faces norte e sul do tronco, na base e a 1,30 e 3,10 m do solo. Discos de madeira foram posteriormente coletados dos locais sondados e o DBM determinado de acordo com o método de imersão em água. Os dados foram submetidos ao teste de normalidade Shapiro-Wilk seguido de análise de variância e análise de correlação de Pearson com α=0,05. Os valores de DBM da balsa diminuiu da base em direção ao topo da árvore, enquanto a profundidade de penetração do Pilodyn foi inversamente proporcional. A correlação entre a profundidade de penetração do Pilodyn e o DBM foi fraca na base do tronco (R^2=0,46), mas forte (R^2=0,72) nos pontos de 1,30 e 3,10 m. O método Pilodyn foi suficientemente confiável que permitiu o desenvolvimento de uma equação para a determinação indireta do DBM do pau-de-balsa considerando o valor da profundidade de penetração a 1,30 m como uma das variáveis.*
Palavras-chave: *Ochroma pyramidale, melhoramento florestal, silvicultura.*

INTRODUCTION

Balsa (*Ochroma pyramidale* (Cav. ex Lam.) Urb.; *Malvaceae*) is a native Amazonian species with occurrence in Brazil and some neighboring countries. Balsa trees grow to a maximum height of 25 to 30 m, with diameters of 0.70 to 1.00 m, and the low-density high-resistant wood are widely in aeronautical and nautical industries (ROJAS, 2011). However, the application with the most compelling environmental appeal is in the area of wind energy, particularly in the manufacture of rotor blades for

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wind turbines. The blades are typically of sandwich construction comprising a soft core of foam or balsa wood embedded between two high-density outer face sheets, and their advanced structural design has led to substantial improvements in the performance and efficiency of wind turbines (MIDGLEY et al., 2010). In addition, balsa wood is a promising alternative base material for the furniture industry since it can be used with advantage in the production of plywood and laminates (EMPRESA MATO GROSSENSE DE PESQUISA ASSISTENCIA E EXTENSAO RURAL, 2009).

Although, balsa wood is considered a low-density material, the commercial market has set specific density standards requiring that basic wood density (BWD) should be within the range 150 to 160 kg m^{-3} at the time of harvest. According to OLIVEIRA et al., (2017), balsa plantations located in the Brazilian state of Mato Grosso comprised individuals with wood densities of 195 and 239 kg m^{-3} for 4- and 14-year old trees, respectively. Considering that BWD is fundamental in assessing the quality of the product, the search for non-destructive methods of evaluating this variable is a matter of primary concern in forestry. The main aim of such research is to maintain the integrity of sampled individuals so that elite genotypes can be selected for improvement programs without sacrificing the trees.

The Pilodyn instrument was originally developed to assess the resistance of structural timber and to provide an indication of the extent of any deterioration, but it has since been used to estimate BWD in environments where other test procedures are impracticable. Comparative studies between the Pilodyn method and other techniques have been carried out on eucalyptus, and satisfactory BWD evaluations were obtained when trunks were probed at 1.5 m from the ground (PÁDUA et al., 2019).

The indirect determination of BWD using the Pilodyn method is advantageous because the instrument is compact, robust and easy to handle and transport (CUELLAR et al., 2018). Furthermore, the reliability of the data provided by the Pilodyn technique allows probing to be performed *in situ*, thereby maintaining the integrity of the sampled specimens. In view of the above, the present study aimed to evaluate the efficiency of the Pilodyn method for the indirect measurement of BWD in balsa wood.

MATERIALS AND METHODS

Twenty adult balsa trees were randomly selected in a plantation of approximately 1.1 ha located in the municipality of Alta Floresta, MT, Brazil, situated some 13 km from the urban area (-9.7720685, -56.0331266). The plantation was established in 2009 using seedlings provided by the Flora Sinop nursery (Sinop, MT, Brazil) and, after 12 years of cultivation, the trees were in good phytosanitary condition with an average height of 17 ± 2.47 m and a mean diameter at breast height (DBH) of 19.6 ± 2.16 cm.

A Pilodyn 6 J Forest instrument (Proceq, Zurich, Switzerland; distributed by TerraGes, Campo Maior, Portugal) was employed to probe the trees at different heights. The Pilodyn device was operated by placing it against the tree trunk at an angle of 90º and shooting a blunt spring-loaded steel pin into the wood with energy of 6 J. The penetration depth of the probe, which is related inversely to the density of the wood, was read on the scale displayed on the side of the instrument.

Each of the trees (n = 20) was probed on both north and south faces of the trunk at the base and at heights of 1.30 m (standard height for DBH measurement) and 3.10 m. Small areas of bark (5 x 5 cm; 25 cm^2) were removed from the three pairs of diametrically opposed probing points, and two values of penetration depth (cm) were read at each point with the Pilodyn instrument held directly against the wood. In this manner, a total of 120 penetration depths were collected and the average value at each probing point was calculated.

Following the *in situ* tests with the Pilodyn device, 5 cm wood discs were collected from each probing point, packed in individual plastic bags to conserve moisture, labeled appropriately and transported to the laboratory. In order to determine BWD, blocks (5 cm long x 2 cm wide x 3 cm high) were cut from the discs in the axial, tangential and radial directions with the aid of a band saw. The volume V (cm^{-3}) of each wood block was determined by measuring the volume of liquid displaced by the block when it was totally immersed in a water-filled container, also known as the Archimedes principle. The blocks were subsequently dried in a forced-air oven at 103 ± 2 °C and weighed to constant dry mass DM (g). The value of BWD (g cm^{-3}) was calculated according to equation 1 (ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS, 1997).

$$BWD = DM/V \qquad \text{Eq. 1}$$

Data were submitted to the Shapiro – Wilk normality test followed by analysis of variance (ANOVA; F test). The correlation between the Pilodyn probe penetration depth and BWD was investigated using Pearson's statistics, and the strength of the relationship between the two variables was expressed by the coefficient of determination (R^2). For all evaluations, the statistical significance level α was set at 0.05.

RESULTS AND DISCUSSION

The BWD values of balsa wood decreased slightly in the direction from the base to the top of the tree; although, no significant differences (P > 0.05; ANOVA) in this variable were observed between the sampling points at the base of the trunk and at heights of 1.30 and 3.10 m (Figure 1A; Table 1). BWD is an important variable in the characterization and classification of wood, and values vary depending on the age of the tree and in both the radial (core-bark) and longitudinal (base-top) directions (SANGUMBE & ALBERTO, 2020). Depending on the species, BWD in the longitudinal direction may either decrease from the base to the top or show alternating values (PANSHIN & DE ZEEUW, 1980; SANGUMBE & ALBERTO, 2020). However, the most common BDW distribution profile in the longitudinal direction involves a reduction in wood density from the base up to around 25 or 50% of the commercial height of the tree, following which the variable may stabilize,

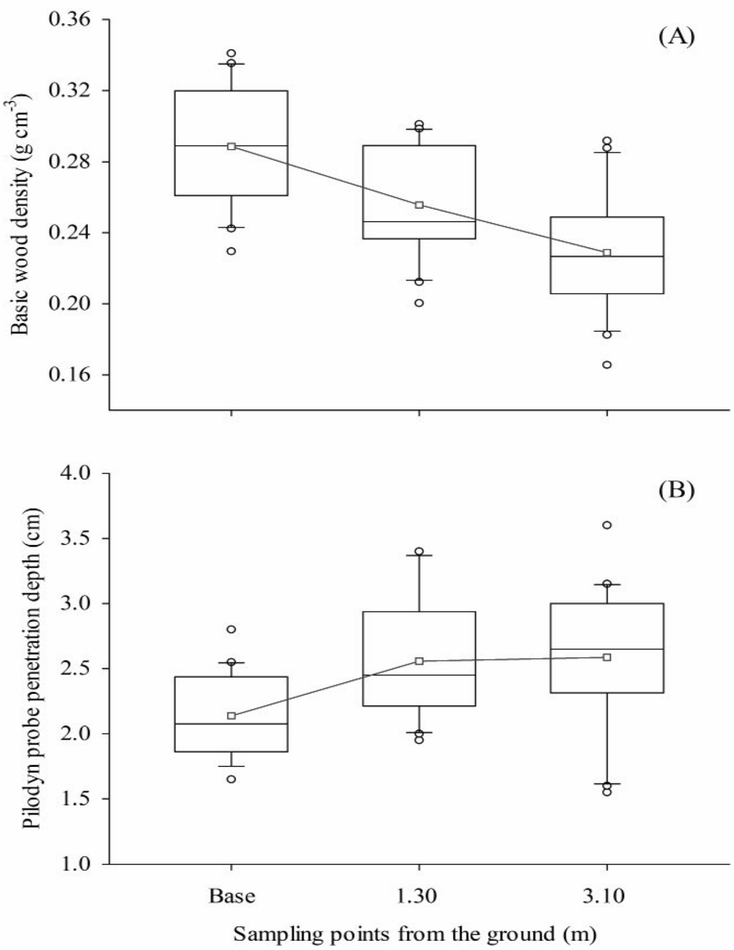

Figure 1 - Characteristics of balsa wood determined in the longitudinal direction at different sampling/probing points from the ground showing: (A) basic wood density (BWD), and (B) Pilodyn probe penetration depth.

Table 1 - Basic wood densities of balsa wood determined at different sampling points on 12-year old trees.

Sampling point (height from the ground)	--------BWD--------			
	Mean* g cm^{-3}	SD g cm^{-3}	Error g cm^{-3}	CV %
Base	0.289	0.033	0.007	11.36
1.3 m	0.246	0.030	0.006	12.18
3.1 m	0.227	0.031	0.007	13.86

Abbreviations: BWD, basic wood density; SD, standard deviation; CV, coefficient of variation.
*Differences between the mean BWD values are not statistically significant according to ANOVA at 5% probability.

as observed in *Pinus patula* Schltdl. & Cham. (RIOS et al., 2018), or increase or decrease as reported by HSING et al., (2016) for clones of eucalyptus hybrids (*Eucalyptus grandis* x *E.urophylla*). In the present study, some balsa trees exhibited alternating BWD values and this can be explained by the genetic variation within the study population since the specimens originated from sexual reproduction between unknown matrices. Thus, disparities rather than a regular pattern of BWD in the longitudinal direction are to be expected, as previously highlighted by MAGALHÃES et al., (2020). Despite the inconsistent BWD patterns presented by some balsa individuals in the longitudinal direction, the density values at different sampling points were similar according to ANOVA. Interestingly, JESUS et al., (2019) described that 8-year old specimens of a hybrid clone of eucalyptus cultivated at two different sites in the state of Bahia presented similar BWD values, indicating that basic density was not affected by environmental conditions and that the trees were able to adapt to moderate edaphoclimatic variations.

The depth of penetration of the Pilodyn probe into balsa wood was inversely proportional to BWD (Figure 1B) such that penetration was greater in wood with a lower density, as observed previously (KOTÁSKOVÁ et al., 2019). Table 1 shows that the BWD of balsa wood was not influenced significantly by the height of the sampling point. Nevertheless, the standard deviation and error values were minimal for BWD measurements made at points located 1.3 m from the ground, indicating that wood density assessed at DBH would likely be the most reliable. Furthermore, evaluation of the probe penetration depth at 1.3 m from the ground appears to be standard considering that such measurements were carried out on 1030 trees of jabon (*Neolamarckia cadamba* (Roxb) Bosser), a timber species native to China, Southeast Asia and Australasia (ANNA et al., 2020). PÁDUA et al., (2019) also reported that the best negative correlation between BWD and Pilodyn probe penetration depth in a hybrid eucalyptus clone was obtained when measurements were performed at 1.5 m high (close to that employed in our study) rather than at lower probing points.

In the present study, a weak negative correlation (R^2 = 46%) between Pilodyn probe penetration depth and the BWD of balsa wood was observed when probing was performed at the base of the tree trunk (Figure 2A). Weak correlations between the two variables have been reported for other structural timber species such as European spruce (*Picea abies* (L.) H. Karst.) (ROHANOVÁ, 2020) and *N.cadamba* (ANNA et al., 2020), and also for eucalyptus when sampling was performed at heights lower than the DBH (PÁDUA et al., 2019). In contrast, we detected strong negative correlations between probe penetration depth and the BWD of balsa wood when probing was performed at 1.3 and 3.1 m from the ground (R^2 > 70%; Figures 2B and C, respectively), a finding that is in agreement with the results reported by PÁDUA et al., (2019).

The error (E_r) expressed in the relationship between Pilodyn probe penetration depth and BWD was much lower at the sampling points of 1.3 and 3.1 m from the ground in comparison with that at the base of the tree trunk (Table 2). However, it is important to emphasize that the Pilodyn equipment must be used in a secure environment in order to prevent discomfort and/or injury to the operator and to allow assessments to be made in a safe, efficient and expeditious manner. Although, the probing point of 3.10 m from the ground is adequate, it is impracticable because work at this height requires additional safety equipment. On this basis, we propose

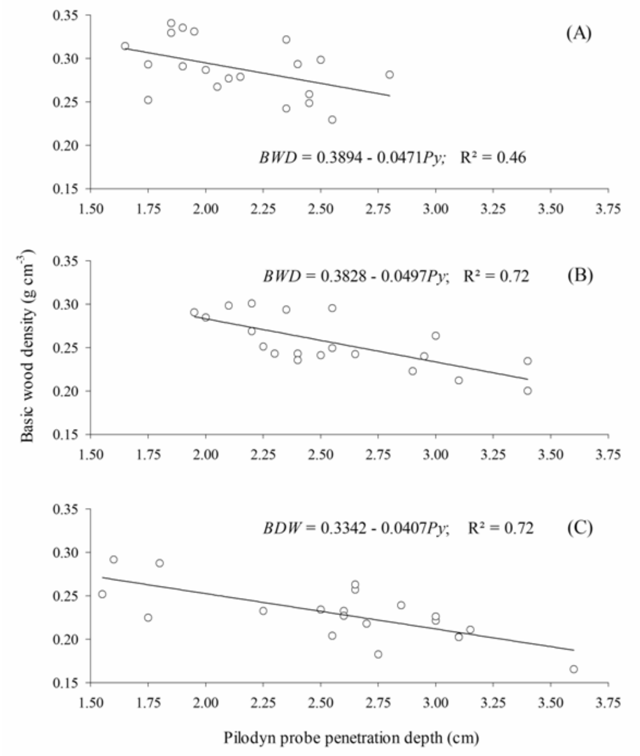

Figure 2 - Linear relationships between basic wood density (*BWD*) and Pilodyn probe penetration depth (*Py*) determined at: (A) the base of the tree trunk, (B) 1.30 m from the ground, and (C) 3.10 m from the ground.

that an indirect assessment of the BWD of balsa wood may be obtained by application of equation 2 in which *Py* (cm) is the penetration depth of the Pilodyn probe determined at 1.3 m from the ground.

$$BWD = 0.3828 - 0.0497Py \quad \text{Eq. 2}$$

The Pilodyn method is considered an indirect non-destructive approach but it is more appropriate to view it as semi-destructive technique because removal of the bark and penetration of the pin into the wood leave lesions in the tree trunk that are

Table 2 - Measures of dispersion referring to the equations describing the relationship between Pilodyn probe penetration depth and basic wood density of balsa wood at different sampling points.

Sampling points (height from the ground)	Mean g cm^{-3}	SD g cm^{-3}	Error g cm^{-3}	E_r%	CV %
Base	0.292^{ns}	0.015	0.003	5.98	5.21
1.3 m	0.261^{ns}	0.022	0.004	0.95	8.28
3.1 m	0.226^{ns}	0.022	0.005	0.13	9.95

Abbreviations: BWD, basic wood density; SD, standard deviation; E_r, error expressed in the relationship between Pilodyn probe depth and BWD; CV, coefficient of variation.

^{ns} Differences between mean values are not statistically significant.

susceptible to insects and pathogens (KOTÁSKOVÁ et al., 2019). However, the wounded area can be easily treated with appropriate fungicide solutions using the brushing method in order to prevent or eradicate wood-destroying fungi.

CONCLUSION

Probing with a properly calibrated Pilodyn instrument is a rapid and efficient method of estimating the BWD of balsa wood for both research and commercial purposes. Investigation of the relationship between BWD and Pilodyn probe penetration depth measured at various heights on mature balsa trees has shown that assessments made at 1.3 m above the ground are highly reliable and allow the operator to work in safety.

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DECLARATION OF CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

AUTHORS' CONTRIBUTIONS

All authors contributed equally to the study.

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